



UPPSALA  
UNIVERSITET

*Digital Comprehensive Summaries of Uppsala Dissertations  
from the Faculty of Science and Technology 1145*

# Characterizations of ground flashes from tropic to northern region

ZIKRI ABADI BAHARUDIN



ACTA  
UNIVERSITATIS  
UPSALIENSIS  
UPPSALA  
2014

ISSN 1651-6214  
ISBN 978-91-554-8946-5  
urn:nbn:se:uu:diva-222838

© Universiti Teknikal Malaysia Melaka

Dissertation presented at Uppsala University to be publicly examined in Högssalen, Ångström Laboratory, Lägerhyddsvägen 1, Uppsala, Tuesday, 3 June 2014 at 10:00 for the degree of Doctor of Philosophy. The examination will be conducted in English. Faculty examiner: Professor Farhad Rachidi (École polytechnique fédérale de Lausanne EPFL).

### **Abstract**

Baharudin, Z. A. 2014. Characterizations of ground flashes from tropic to northern region. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 1145. 78 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-554-8946-5.

This thesis portrays new information concerning the cloud-to-ground (CG) lightning flashes or ground flashes produced by thunderclouds. It emphasizes the importance of characterizing lightning studies as the relationship between lightning mechanisms, and of incorporating the influence of geographical location, latitude and storm type. Sweden, Malaysia and USA were chosen as the main locations for field experiments in 2009 to 2011 to gather a significant number of negative and positive CG flashes. This work provided data on a total of 1792 CG lightning flashes (1685 negative and 107 positive ones) from a total of 53 thunderstorms by monitoring both the slow and the fast electric field and the narrowband radiation field at 3 and 30 MHz signals simultaneously. This thesis is comprised of: (i) the relationship of the Low Positive Charge Region (LPCR) and Preliminary Breakdown Pulse (PBP) trains to the occurrence of negative CG, (ii) slow field changes generated by preliminary breakdown processes in positive and negative ground flashes, and (iii) the occurrence of positive and negative ground flashes. It was revealed that the PBP train appeared have a higher strength in the in Sweden. The strength of the PBP train was caused by the LPCR; in contrast, weak PBP trains were characteristic in tropical countries constituting insignificant LPCR and needing little energy to break the “blocking” agent to allow the flash to propagate downward to the ground. The second contribution concerns the characteristics of the PBP train mentioned; this includes novel information for Malaysia. Further, it is stated that there are some different characteristics in the PBP trains in Johor, Malaysia and Florida, USA. The studies of slow field changes generated by preliminary breakdown processes clarifies unclear features concerning the starting position of slow field changes generated by preliminary breakdown processes in positive and negative ground flashes. It was found that the slow field changes did not occur before the initial process of the commencement of preliminary breakdown. Single-station electric field measurements incorporating narrowband radiation field measurement and high resolution transient recording (12 bits) with an accuracy of several nanoseconds, allows one to distinguish between the intracloud activities and the preceding processes of ground flashes. The results for the interstroke intervals, amplitude distribution of subsequent return-stroke (SRS) and the number of strokes per flash in the tropics, subtropics and northern regions were similar. Finally, a significant number of positive return-stroke (RS) electric fields provided statistically significant information on the characteristics of these strokes.

*Keywords:* Positive/negative cloud-to-ground lightning flashes, Initiation position, slow field changes, close ground flashes, preliminary breakdown process

*Zikri Abadi Baharudin, Department of Engineering Sciences, Box 534, Uppsala University, SE-75121 Uppsala, Sweden.*

© Zikri Abadi Baharudin 2014

ISSN 1651-6214

ISBN 978-91-554-8946-5

urn:nbn:se:uu:diva-222838 (<http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-222838>)

*Dedication to:  
Professor Vernon Cooray,  
Dr. Mahbubur Rahman,  
Dr. Fernando Mahendra,  
my wife Sazillah,  
our children Adeeb, Asheef,  
and Ahmad Saidnursi,  
and my beloved mother, Zinun.*



# List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

- I **Z. A. Baharudin**, N. Azlinda Ahmad, M. Fernando, V. Cooray, J. S. Mäkelä, (2012). Comparative study on preliminary breakdown pulse trains observed in Johor, Malaysia and Florida, USA. *Atmospheric research*, 117, 111 – 121.
- II **Z. A. Baharudin**, M. Fernando, N. Azlinda Ahmad, J. S. Mäkelä, M. Rahman, V. Cooray, (2012). Electric field changes generated by the preliminary breakdown for the negative cloud-to-ground lightning flashes in Malaysia and Sweden. *Journal of Atmospheric and Solar Terrestrial Physics*, 84 – 85, 15 – 24.
- III **Z. A. Baharudin**, V. Cooray, M. Rahman, P. Hettiarachchi, N. Azlinda Ahmad. Electric field changes generated by the preliminary breakdown for the positive cloud-to-ground lightning flashes in Sweden. *Submitted to Journal of Atmospheric and Solar-Terrestrial Physics*, April 2014.
- IV **Z. A. Baharudin**, N. Azlinda Ahmad, J. S. Mäkelä, M. Fernando, V. Cooray, (2014). Negative cloud-to-ground lightning flashes in Malaysia. *Journal of Atmospheric and Solar-Terrestrial Physics*, 108, 61 – 67.
- V **Z. A. Baharudin**, V. Cooray, M. Rahman, P. Hettiarachchi, N. Azlinda Ahmad. On the characteristics of positive lightning ground flashes in Sweden. *Submitted to Journal of Atmospheric and Solar-Terrestrial Physics*, August 2013.

Reprints were made with permission from the respective publishers.

Other contributions of the author, not includes in this thesis

- VI **Z. A. Baharudin**, M. Fernando, N. Azlinda Ahmad, V. Cooray, J. S. Mäkelä, (2010). Comparative study on preliminary breakdown pulse trains observed in Malaysia and Florida. *In: Proc. International Conference of Lightning Protection (ICLP), Cagliari, Italy, 2010.*
- VII N. Azlinda Ahmad, M. Fernando, **Z. A. Baharudin**, M. Rahman, V. Cooray, Ziad Saleh, Joseph R. Dwyer, Hamid K. Rassoul, (2010). The first electric field pulse of cloud and cloud-to-ground lightning discharges. *Journal of Atmospheric and Solar Terrestrial Physics*, 72, 143 – 150.
- VIII N. Azlinda Ahmad, **Z. A. Baharudin**, M. Fernando, V. Cooray. Radiation field spectra of long-duration cloud flashes. *Submitted to Journal of Atmospheric Science Letter*, December 2013.
- IX N. Azlinda Ahmad, Fernando, **Z. A. Baharudin**, M. V. Cooray, Ahmad. H., Abdul Malek, Z., (2010). *The characteristics of narrow bipolar pulses in Malaysia.* Submitted to *Journal of Atmospheric Science Letter*, December 2013.
- X N. Azlinda Ahmad, Z. A. **Baharudin**, M. Fernando, V. Cooray. Some features of electric field waveform of narrow bipolar pulses. *In: Proc. International Conference of Lightning Protection (ICLP), Cagliari, Italy, 2010.*

# Contents

1	Introduction .....	11
1.1	Motivation.....	11
1.2	Objective and summary of contribution of the thesis .....	12
2	Cloud-To-Ground Lightning Flashes From Lightning–Producing Cumulonimbus.....	15
2.1	Terminology of cloud-to-ground lightning flashes .....	15
2.1.1	Downward-moving process .....	18
2.1.2	Upward-moving process .....	19
2.2	Modes of Charge Transfer for CG .....	21
2.2.1	Dart-leader – return-stroke sequence .....	21
2.2.2	Continuing Current .....	22
2.2.3	Lightning M-component.....	22
2.3	Background of remote measurements of lightning generated electric fields .....	23
3	Electric Field Measurement.....	27
3.1	Antenna systems for determining an electrostatic and broadband radiation field .....	27
3.1.1	Electronic circuitry for the measurement of slow and fast electric fields.....	30
3.1.2	Calibration of antenna.....	32
3.2	Narrowband radiation field antenna system.....	38
3.3	Data .....	40
4	Preliminary breakdown pulse trains at different geographical regions.....	41
4.1	The relationship of LPCR and PBP trains with the occurrence of negative CG (Paper 1 and Paper 4) .....	41
4.2	Characteristics of the PBP train (Paper 1).....	47
5	Electric field changes generated by the preliminary breakdown pulse for CG flashes (papers 2 and 3).....	53
6	Statistical information for cloud-to-ground lightning flashes from the tropics to northern regions (papers 4 and 5).....	59
6.1	Negative Ground flashes (Paper 4) .....	60

6.2	Positive ground flashes (Paper 5).....	61
7	Conclusion and recommendation .....	63
	Svensk sammanfattning .....	65
	Acknowledgements.....	67
	Bibliography .....	69



# Abbreviations

BIL	initial breakdown, intermediate, stepped leader
CG	cloud-to-ground flash
CC	cloud-to-cloud
HF	high frequency
IC	Intracloud
kHz	kilo hertz
LPCR	Low Positive Charge Region
MHz	mega hertz
$N$	negative charge region
$N_+$	positive field changes
$N_-$	negative field changes
$P$	positive charge uppermost region
$p$	LPCR
PBP	preliminary breakdown pulse
RF	radio frequency
RS	return-stroke
SRS	subsequent return-stroke
$\Delta T$	pre-starting time



# 1 Introduction

## 1.1 Motivation

The phenomenon of lightning has been the subject of intensive studies by electrical engineers and researchers. Its behavior is fairly predictable in general terms, although the exact description of the physical processes for specific instances is not predictable. The interpretation, and sometimes speculation, is often complicated which owing to the complexity and variability of lightning generation mechanisms. Furthermore, as there is no conclusive evidence that lightning could be prevented, one has to recognize the possibility of a lightning strike and take appropriate measures to make each strike harmless. Lightning protection is, then, the implementation of appropriate actions for the characteristics of the lightning anticipated.

Many of the characteristics of lightning flashes, such as the characteristics of storms (individual or systems), occurrence statistics, pulse structure, number of strokes per flash and the polarity of the charge lowered to the ground, apparently depend on the season, geographical region, latitude and storm type. Year after year, investigators have reported novel findings where lightning characteristics are concerned; these parallel the progress in the development of technology available for lightning electromagnetic field measurements. Characterization of electric fields from electromagnetic field measurements is still considered an important tool for electrical engineers and researchers. This is because the knowledge obtained significantly improves the investigators' understanding of the potential effect of deleterious coupling of lightning fields with various objects especially to sensitive electronic devices.

Through the characterization of field data, one can extract information such as the time dependence of the voltage or current, which can be used for modeling and as an input for the computation of lightning electromagnetic fields. Any lightning model is actually necessarily an approximate mathematical construct designed to reproduce certain aspects of the physical processes involved in the lightning discharge. The basic assumptions of the model should be consistent with both the expected outputs of the model and the availability of quantities required as an input to it.

## 1.2 Objective and summary of contribution of the thesis

The main objective in writing this thesis was to characterize the availability of physical information in the processes underlying cloud-to-ground (CG) lightning flashes (that is, negative and positive CG flashes) by using remote measurements of lightning-generated electric fields. As mentioned in Section 1.1, the occurrences of CG flashes depend on the geographical region, as well as other related factors such as the latitude and type of storm. Hence, this thesis has considered those factors when acquiring data from three different locations: Sweden, Malaysia and USA. In general, research has been carried out with the intention of generating valuable data to address the lack of information in previous studies on CG flashes. The contributions are summarized in five publications as follows:

**Paper 1:** Comparative study on preliminary breakdown pulse trains observed in Johor, Malaysia and Florida, USA

The objective of this paper was to investigate the relationship between the preliminary breakdown pulse and the first return-stroke (RS) electric fields using high resolution data recorded from thunderstorms in Malaysia and USA (both data were recorded in 2009). These data were compared with other available results from Sweden, Finland, Sri Lanka and USA (recorded by Nag and co-workers in 2008 and 2009). This study revealed that the strength of the ground-flash-initiation breakdown process in the cloud, measured against on a comparison with the peak radiation field of the resulting RS, is larger in the northern region (Sweden and Finland) compared to that of the tropical regions (Malaysia and Sri Lanka). Besides, it is known that the initial preliminary breakdown processes in negative CG flashes in Malaysia are different from those in USA. These are described.

**Paper 2:** Electric field changes generated by the preliminary breakdown for the negative cloud-to-ground lightning flashes in Malaysia and Sweden

In this paper, the objective was to clarify the unknown features of the electric field changes preceding negative first return flashes, and especially in determining the position of slow field (electrostatic field) changes that associated in the preliminary breakdown process. This study shows that the position of slow field changes are always found occur after the first preliminary breakdown pulse (PBP) or does not start before the PBP.

**Paper 3:** Electric field changes generated by the preliminary breakdown pulse for positive lightning ground flashes in Sweden

This paper had a similar aim that outlined for Paper 2, but the main consideration is the positive CG flash in this instance. This is the first time a study on the electric field changes, generated by the preliminary breakdown

for positive CG flashes, is found to be associated with the slow field changes in the preliminary breakdown process. This result is consistent with that in Paper 2, where the slow field changes do not start before the preliminary breakdown process.

**Paper 4:** Negative Cloud-To-Ground Lightning Flashes in Malaysia

The main objective of this paper was to provide statistical information on negative CG flashes in Malaysia since there was no available information previously in Malaysia on this. The study has found that the results for CG flashes in Malaysia, USA, Sweden, Sri Lanka and Brazil are similar where all characteristics are concerned (that is, time intervals, the ratio of the subsequent return-stroke (SRS) to the first RS, and the number of strokes per flash).

**Paper 5:** The characteristics of positive cloud-to-ground flashes in Uppsala, Sweden

Insufficient positive ground flashes have caused difficulty in collecting a large sample of electric fields generated by positive ground flashes. The purpose of this paper is to present a significant number of positive RS electric fields so that statistically significant information on stroke characteristics could be gathered. From these electric field records, we have reported the number of strokes per flash, inter-stroke intervals and the amplitude distribution of subsequent return strokes (SRS).



## 2 Cloud-To-Ground Lightning Flashes From Lightning–Producing Cumulonimbus

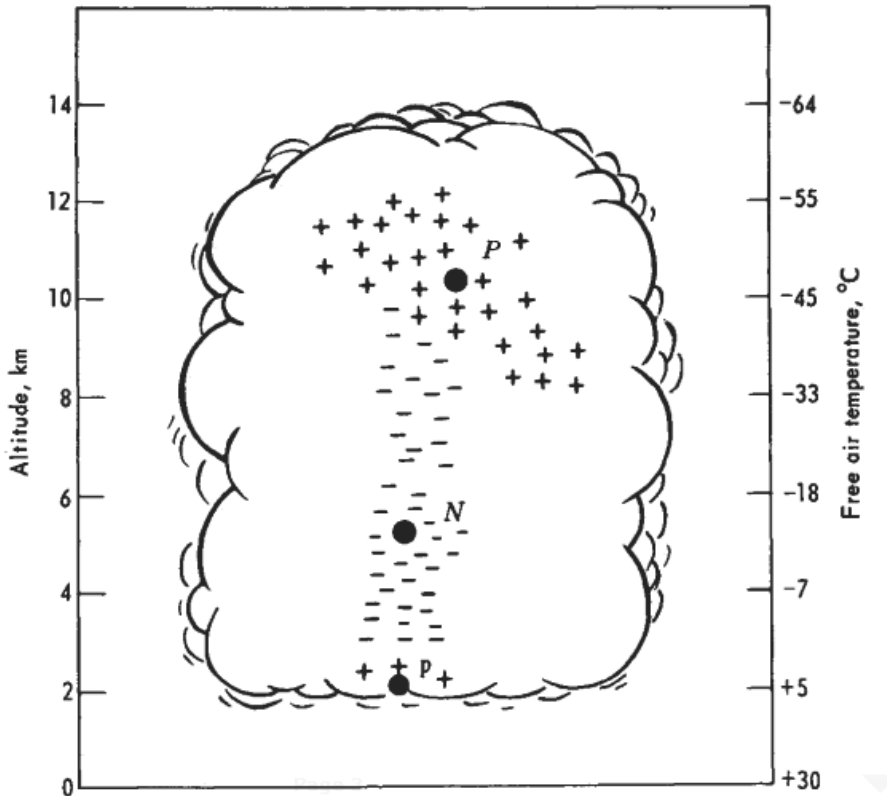
### 2.1 Terminology of cloud-to-ground lightning flashes

Lightning and lightning discharges within a cloud are usually termed “lightning flashes” or simply called “flashes”. They can be intracloud (IC)), cloud-to-cloud (CC), cloud-to-ground (CG), or surrounding air discharges, the latter also being known as air discharges. Lightning flashes are massive electrostatic discharges caused by unbalanced electric charges in the atmosphere, resulting in a strike, from IC, CC or CG discharges and accompanied by the loud sound of thunder. The lightning flash can be defined as a transient, high-current electric discharge whose path length is generally measured in kilometers. Lightning occurs when some region of the atmosphere attains a sufficiently large electric charge, and therefore electric fields, to instigate the electrical breakdown of the air.

The most common sources of lightning is the thundercloud, usually formed by cumulonimbus, where the lightning is associated with the convective mechanism in the cloud systems, ranging from 3 to 20 km in vertical extent, while the horizontal dimension of active air-mass thunderstorms varies from 3 km to 50 km or more<sup>[81,100]</sup>. Basically, the structure of the thundercloud was found to be a tripolar electrostatic. A tripolar electrostatic cloud structure is one where the body of cloud is essentially divided into the positive charge uppermost region (net positive charge), followed by the negative charge region (net negative charge) below it or at its midlevel, and an additional small pocket of positive charge, also known as Low Positive Charge Region (LPCR) at the bottom of the cloud. Figure 1 shows an example of the probable distribution of cloud charges adapted from the measurements obtained by Malan<sup>[53]</sup>.

Thunderclouds are large atmospheric heat engines, with input energy from the sun and water vapor as their primary heat-transfer agent. Hence, they may underlie the mechanical workings of the winds (vertical or horizontal) generated by a storm, causing an outflow of condensation (in the form of rain and hail) from the bottom of the cloud and small ice crystals

from the top of it, along with electrical discharges (IC,CC,CG), including corona, lightning, sprites, elves, and blue jets. However, the processes that operate in a thundercloud to produce the actions mentioned above are poorly understood owing to the fact that they are a large, complex and short-lived phenomena<sup>[48,81]</sup>. Interestingly, lightning also occurs during snow storms (thundersnow)<sup>[9,92,93,94]</sup>, volcanic eruptions<sup>[2,10,55]</sup>, and nuclear explosion<sup>[16,101]</sup>.

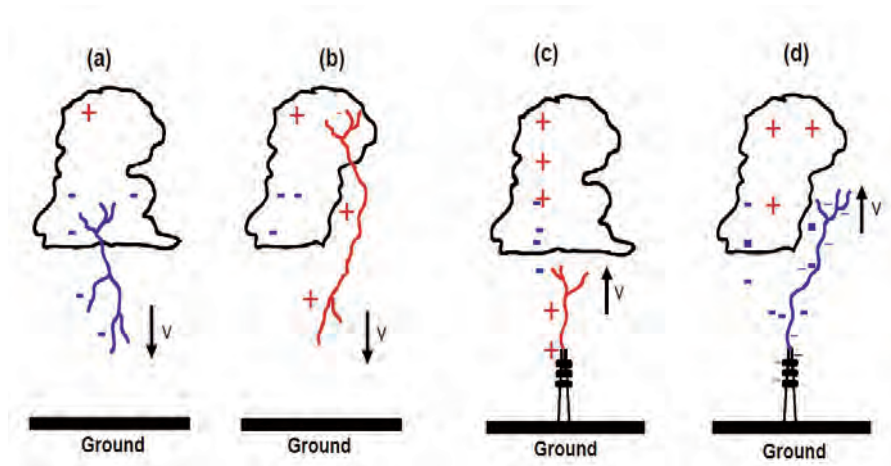


**Figure 1.** The probable distribution of thundercloud charges, *P* – positive charge uppermost region, *N* – negative charge region and *p* – Low Positive Charge Region (LPCR) for a South African thundercloud according to Malan (1952, 1963). Adapted from [100]

Ground flashes or CG are the best known of all the different types of lightning since they strike the ground, thereby posing the greatest threat to life and property. CG are lightning discharges between a cumulonimbus cloud and the ground; they can generate four types of possible flashes as defined comprehensively by K. Berger<sup>[12,13]</sup> and discussed in detail by Rakov and Uman<sup>[81]</sup>, and as illustrated in Figure 2. The various types of ground flashes can be viewed in terms of: (i) the polarity of the charges in the cloud from



where the leader is initiated or to the place where it propagates, or (ii) the direction of the leader. It is also noticed that the portion of polarity (downward or upward) denotes the polarity of the resultant current to the ground.

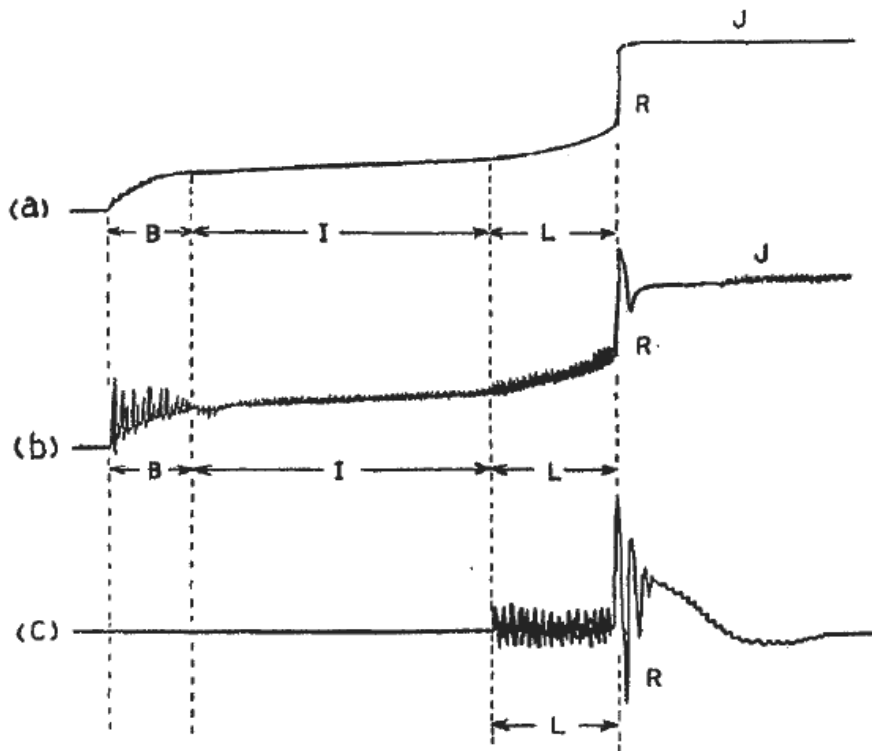


**Figure 2.** Types of cloud-to-ground lightning flashes: comprising (a) downward negative lightning, (b) downward positive lightning, (c) upward negative lightning, and (d) upward positive lightning.

The first type of ground flash denoted in Figure 2(a) shows downward negative lightning. This predominates in structures with heights of less than about 100 m. It is believed that 90 % of global ground flashes are the transport of negative charges to the ground. The peak current (first RS) is about 30 kA. Typically, the range of average of negative ground flash may be comprised of three to five strokes within a flash<sup>[82]</sup>, however they have been observed to occur as many as 26 times in one flash<sup>[46]</sup>. According to the classification of Berger et al<sup>[13]</sup> as depicted in Figure 2(b), downward positive lightning accounts for about 10 % or less of global CG lightning flashes. Positive ground flashes, however, give rise to larger currents and larger positive charge transfer than their more numerous counterparts, negative ground flashes<sup>[13,48]</sup>. Upward negative lightning, illustrate in Figure 2(c) was first observed at the Empire State Building in New York City,<sup>[35]</sup> and was thought to be associated with high structures. For example, according to Berger,<sup>[13]</sup> who conducted lightning observations at Mt. San Salvatore in Switzerland with measurement equipment (in the form of 70 and 80-meter masts) located at 650 m, at the top of the mountain, his equipment was stuck by 1196 flashes in 11 years. Of these, 75 % were determined to be negative upward flashes, only about 11 % were negative downward ones, and the remaining 14 % were identified as positive upward flashes, illustrated in (d).

### 2.1.1 Downward-moving process

The earlier studies by Clarence and Malan<sup>[15]</sup> in 1957 suggested that the ground flashes usually began with three successive discharge processes (see Figure 3) which are known as the initial breakdown and also sometimes referred to as the preliminary breakdown; these are followed by a pre-discharge, which comes prior to the first return-stroke in a flash, the so-called stepped leader<sup>[81,100]</sup>. Sometimes, stepped leaders occur immediately after the preliminary breakdown process but that can also appear after the so-called intermediate stage, which may last up to 400 ms.



**Figure 3.** Example of the characteristic signatures of the signals for ground flash used by Clarence and Malan (1957) to introduce the so called BIL structure of the electric field prior to the first return-stroke: (a) The electrostatic field at 5 km. (b) The electrostatic field at 50 km. The relative amplitude of the signature for R has been reduced. (c) The radiation field at 500 km. The time is nonlinear, with the duration of B, I, and L being 2 – 10, 0 – 400, and 4 – 30 ms, respectively. This illustration is adapted from Clarence and Malan<sup>[15]</sup>.

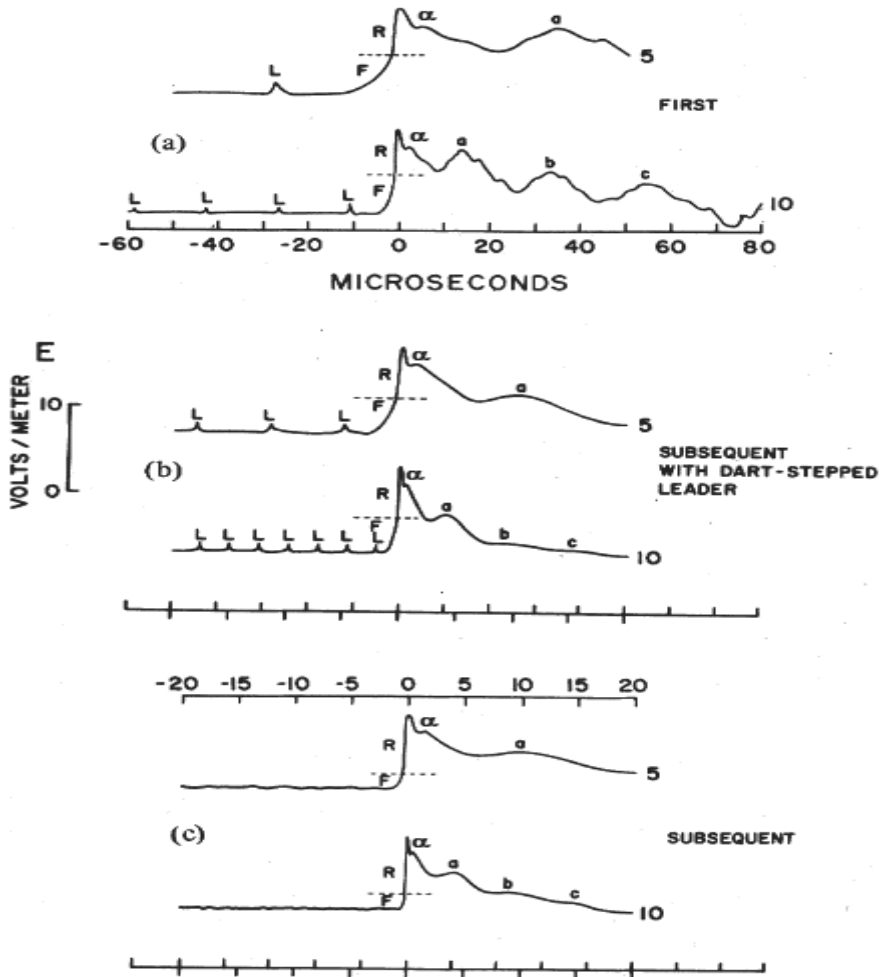
For convenience, the negative CG mechanism is used to describe the terminology related to CG. Preliminary breakdown is widely believed to com-

mence with a local electrical breakdown between the negative charge center and the Low Positive Charge Region (LPCR) at the base of the thundercloud that may last from a few milliseconds to some tens of milliseconds<sup>[81,101]</sup>. This initial breakdown would serve to mobilize the electric charges that, previously, were attached to ice and water particles. The strong concentration of negative charge at the bottom of the negative charge region would produce electric fields and these could then cause a negatively charged column to be propelled down towards the earth.

The formation of a negatively charged column is called the stepped leader progression, because the column appears to move downwards in luminous steps. By means of high-speed time-resolved photographs<sup>[26,81]</sup>, the typical average speed in a series of discrete luminous steps is  $2 \times 10^5 \text{ ms}^{-1}$  and the length of successive steps is some tens of meters, with the duration of each step being  $1 \mu\text{s}$ . The time interval between the steps was found to be about 20 to 50  $\mu\text{s}$ . The peak current for a pulse associated with an individual step was found to be 1 kA or greater. The stepped leader serves to form a conducting path or channel between a cloud charge source and the ground.

### 2.1.2 Upward-moving process

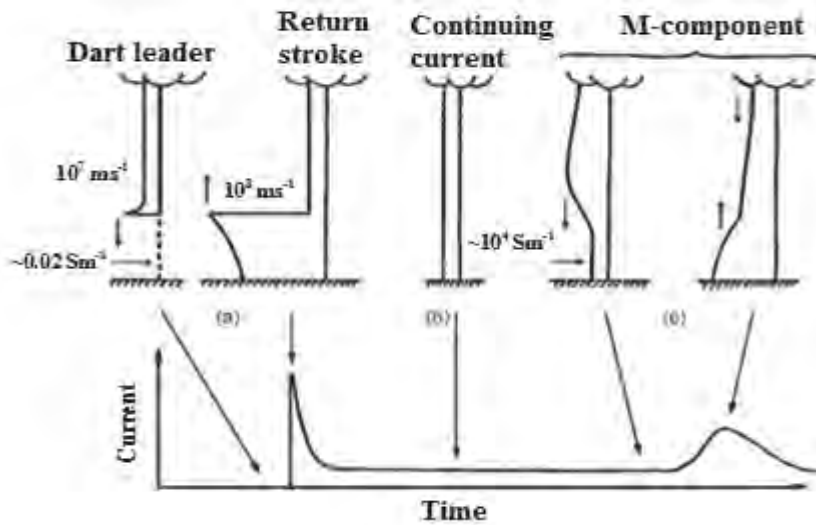
When the stepped leader moving downwards is carrying negative charge near the ground, the electric field at ground level increases steadily. Further, the moment when the stepped leader reaches a height of a few hundred or less meters from the ground, the electric field, particularly at the tip of grounded structures, increases until it exceeds the critical value for the initiation of one or more upward-moving discharges, which are launched from the ground towards the leader tip. These upward-moving discharges are called upward-connecting leaders. One of the upward-connecting leaders may successfully bridge the gap between the ground and the downward leader. When the contact is made between the downward and upward-moving leaders, the first return-stroke (RS) begins and its wave (wavefront) travels upwards, carrying ground potential up towards the cloud along the channel created previously by the stepped leader. Concurrently, the occurrence of a transient enhancement of the channel luminosity below the branch point is often observed; this is referred to as the branch component. The average speed of an upward-moving RS wavefront is typically between one-third and one-half the speed of light over the visible channel. The current measured at the ground rises approximately 10 to 30 kA in a few microseconds and decays to the half-peak value in some tens of microseconds while profiling a number of subsidiary peaks (see Figure 4 showing the subsidiary peaks) which were thought to be associated with the branches.



**Figure 4.** The radiation fields produced by (a) the first RS, (b) a subsequent return-stroke (SRS) preceded by a dart-stepped leader, and (c) a SRS preceded by a dart stepped leader in a lightning discharge to ground. The field amplitude is normalized to a distance of 100 km. The small pulses attributed to the stepped leader (L) are followed by a slow front (F) and an abrupt, fast transition to peak R. Following the fast transition, there is a small secondary peak or shoulder  $\alpha$  and large subsidiary peaks, a, b, and c. Adapted from Weidman and Krider<sup>[104]</sup>.

## 2.2 Modes of Charge Transfer for CG

There are three possible modes of charge transfer to ground in negative lightning SRS. The three modes of charge transfer for negative ground flashes are: (a) dart-leader – RS sequence, (b) continuing currents and (c) M-components (see Figure 5).



**Figure 5.** Schematic of physical mechanism and current versus time waveform for three modes of charge transfer to ground for negative CG lightning flashes during lightning SRS: (a) dart-leader/RS sequence, (b) continuing current, and (c) M component. Adapted from [80].

### 2.2.1 Dart-leader – return-stroke sequence

The stepped leader deposits negative charge along the conducting path between the cloud and ground, while the RS traverses that path, it can either neutralize some negative charges on the stepped leader or deposit some positive charge on the stepped leader channel and in the cloud charge source region. After the first RS has ceased to flow, the ground flash might end, in this case, it is called a single-stroke flash. On the other hand, if additional charge is made available to the top of the channel, the first RS of the ground flash could be followed by a few or more additional RS (SRS); in this instance, the flash is said to be a multiple-stroke flash. In multiple-stroke flashes, each preceding stroke appears to drain charge from higher areas in the negative region of the cloud, carrying the cloud potential earthward once more by the action of the dart-leader. This charge is made available during

the time interval between the previous RS (eg., the end of the first RS) and a higher region of negative charge (eg., the initiation of dart leader) due to the action of the so called J-process and K-process. J-processes are thought to be a relatively slow positive leader extending from the place where the flash originates into the negative charge region<sup>[8,45]</sup>, which consists of a small number of K-process steps. K-processes are relatively fast streamers (recoil streamer) that begin at the tip of the positive leader and propagate towards the origin of the flash in the cloud. In other words, J-processes and K-processes play a role in transporting additional negative charge into and along existing channels in the cloud for the ground flashes. The dart-leader deflects from the previous RS path and forms a new termination on the ground with similar action relating to the attachment process that has been described in the first return stroke process. When the dart-leader contacts with upward-moving leaders from the ground, the SRS may occur and again serves to neutralize the charge leader.

### 2.2.2 Continuing Current

The lightning continuing current is thought to be a flow of impulsive current in the SRS at low levels of tens to hundreds milliseconds. The long duration of the continuing current that exceeds 40 ms is termed as a long continuing current. The continuing current typically exhibits a number of superimposed surges that rise to a peak and fall off to the background current level in some hundreds of microseconds, the peak being generally in the hundreds of ampere range, but occasionally in the kilo-amperes range. These current surges are associated with the enhancements in the relatively faint luminosity of the continuing current channel and are called M-components.

### 2.2.3 Lightning M-component

The term 'M-component' refers to a rapid electric field variation in the continuing current carried by the RS that increases the channel luminosity temporarily<sup>[46,102]</sup>. According to Figure 5, the M-component appears to be a superposition of two waves propagating in opposite directions. The spatial front length is approximately a kilometer from the cloud height.

## 2.3 Background of remote measurements of lightning generated electric fields

Scientists have proven that the use of simultaneous measurement of the electrostatic and radiation field allows the determination of electric field data over the time of a complete lightning flash with suitable time resolution of the rapidly occurring field variation. Previously, Wilson<sup>[105,106]</sup>, Appleton et al.<sup>[11]</sup>, and Schonland and Craib<sup>[85]</sup> were among the pioneers who conducted the measurements of electrostatic field (also known as the slow field) and radiation field (also known as electrostatic field changes or the fast field) from thunderclouds. Their independently conducted results were consistent. Among the conclusions from their studies are the following: (i) The thundercloud is essentially an electric dipole, with a net positive charge located above a net negative charge. Its magnitude can be deduced from measurement of the slow field or fast field change of the thundercloud as a function of horizontal distance, i.e. between the location of the discharge and the measurement station. (ii) Usually a CG lightning flash lowers the negative charge from cloud to ground with an average electric moment (M), the destruction of charge takes place at a level of about 100 Coul-km.

The work of Wilson and of Schonland and Craib was conducted using an antenna connected to a capillary electrometer (a mercury-sulfuric-acid capillary electrometer). The capillary electrometer measures the electric field intensity with a resolution of about 0.1 s. The charge induced on the antenna caused the motion of a drop of sulfuric acid within a capillary tube filled with mercury. The displacement of the acid drop was proportional to the field. On the other hand, Appleton, Watson-Watt, and Herd used an antenna attached to an oscilloscope, in addition to using similar equipment to that of Wilson. By the early 1930s, the combination of slow and fast field measurements of thunderclouds obtained by Wormell<sup>[107]</sup>, Jensen<sup>[40,41,42,43]</sup>, and Haliday<sup>[33]</sup> strengthened and supported the facts determined by previous works, and in particular, the transportation of negative charge was predominant for ground flashes. For example, Schonland and Allibone<sup>[87]</sup> reported at least 95 % of the 404 flashes from 50 South African thunderstorms were caused by negative charge. Similarly, Haliday<sup>[33]</sup> reported that 267 of the flashes measured were found to be negative ground flashes.

The other features determined by the measurement techniques mentioned above concerned the importance of charge amount, flash distance and the polarity of field changes. To this effect, extensive investigations using these methods were performed in the 1950s<sup>[15,51,52,67,68,108]</sup>. The investigators revealed that the majority of lightning flashes associated with slow field changes occurred comparatively slowly, and had the duration of slow sections either between initial sections and RS or latter sections of return-stroke.

Pierce<sup>[68]</sup> had summarized his observation using a capillary electrometer during the summers of 1939 and 1946, then the data obtained in 1947 and 1949 were recorded using an oscilloscope. He also included the data of Wilson (recorded from 1920 to 1924) and Wormell (recorded in 1926 to 1936). He did not, however, specify if the field changes ( $N_+$ —positive field changes or  $N_-$ —negative field changes) were attributable to cloud or ground flashes, or any specific section preceding the first RS. He concluded that the ratios of  $N_+/N_-$  were consistent for the magnitudes of electric field less than 100 V/m since there is no significant change in the magnitude between 0.1 and 100 V/m. However, the positive field changes became increasingly strong for 100 V/m and above.

In 1930s, considerable advancements had been made in lightning measurement techniques, such as the simultaneous electrostatic field and the use of photographic records. Schonland<sup>[86,87]</sup> was the first researcher to make a combination of visual observation and photographic record with an electric field measurement. From correlated data of the field change measurement and photographic measurement, Jensen<sup>[40,41,42,43]</sup> recorded 185 flashes at close distance and reported that most of the ground flashes exhibited positive field change or lowering of negative charge. Clarence and Malan<sup>[15]</sup> were the first investigators to introduce the BIL terminology (discussed in Papers 1 and 2) utilizing a combination of photographic observation with electric field measurements obtained using a field mill<sup>[50]</sup> for slow fields and oscillographic methods (similar to the method of Appleton, Watson-Watt and Herd) to monitor changes in the radiation field.

The excellent observations performed by Kitagawa and his co-workers<sup>[46]</sup> of various electrostatic field changes and lightning properties based on their simultaneous photographic and high time-resolution electric field records that clarified some of the properties of lightning. During that period of time, the most obvious features in their records (see Figure 6) were the abrupt field change caused by the return-stroke (or the known R changes). Furthermore, in Figure 6, C-change arising from continuous current, the M-change from the M-component, the K-change which occurred in the interstroke intervals, and the J-change which was attributed to the so-called junction process occurring in the cloud between strokes, were revealed with success.

Since the 1970s until recently, the concept of remote measurement of electromagnetic field generated by lightning<sup>[39,70,71]</sup> has been used to determine how much lightning occurs within a given region and to find the statistics of discharge parameters that were important in research and in the design of lightning protection. Furthermore, this measurement had become tools with which to provide lightning detection and mapping lightning loca-